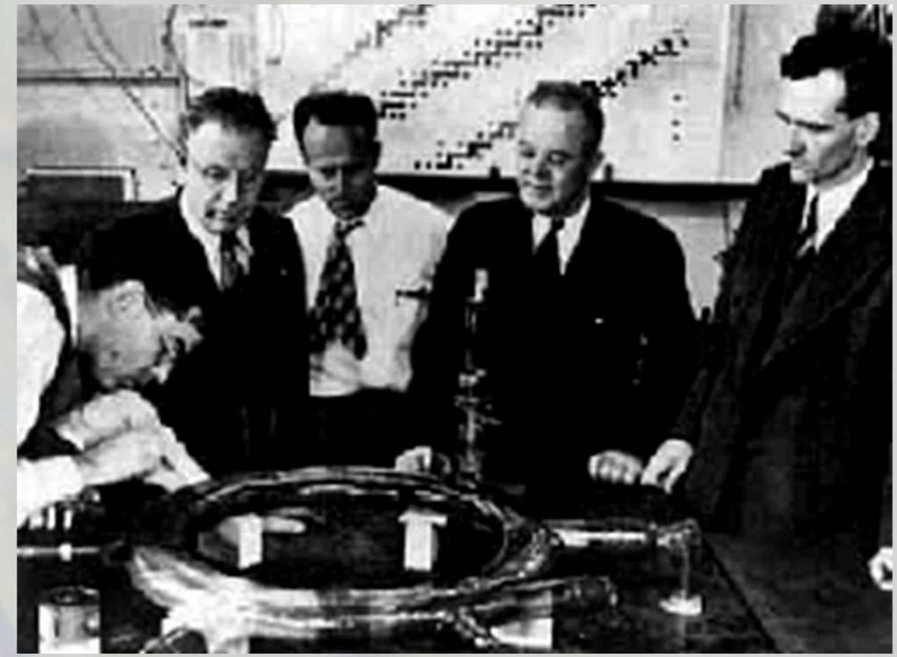
Discovery of Synchrotron Radiation

1947
First observation of synchrotron radiation
70 MeV
GE, Schenectady, NY



Success of Synchrotron Radiation

About 50 synchrotrons in the world

Electrodynamic Intermezzo

Relativistic energy momentum relation: $E^2 = m_0^2 c^4 + p^2 c^2$

"Before" (Classical mechanics until 1901):

$$E_{kin} = \frac{1}{2} m v^2$$

Maxwell formulates his famous set of equations in 1861 linking prior knowledge about electricity (Faraday's law) and magnetism (Gauss' law) to unify them in *electromagnetism:*

ignoring some natural constants these equations are:

$$\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{E} = \rho$$

$$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

With some manipulations these equations postulate that their must exist propagating electromagnetic waves that travel with a velocity *c* that can be derived from known natural constants… this turned out to be light

Electrodynamic Intermezzo

Relativistic energy momentum relation: $E^2 = m_0^2 c^4 + p^2 c^2$

Where did his come from ?

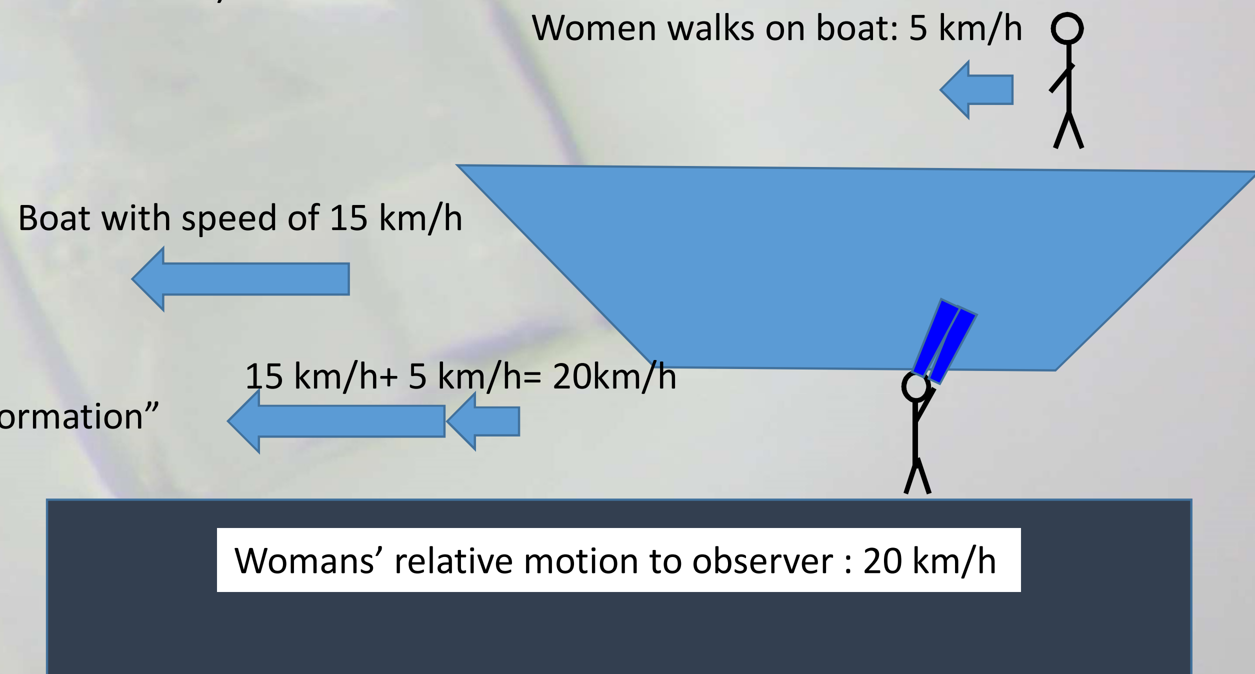
"Before" (Classical mechanics until 1901):

$$E_{kin} = \frac{1}{2} m v^2$$

Classical (Newtonian) mechanics

$\vec{p} = \mathrm{m} \cdot \vec{v}$ (momentum is linear with respect to mass and velocity)

$\vec{F} = \frac{\partial \vec{p}}{\partial t} = \mathrm{m} \cdot \vec{a}$ (force is liner to acceleration and mass)



Galilei transformation "linear transformation"

Electrodynamic Intermezzo

Relativistic energy momentum relation: $E^2=m_0^2c^4+p^2c^2$

"Before" (Classical mechanics until 1901)

$$E = \frac{1}{2}mv^2$$

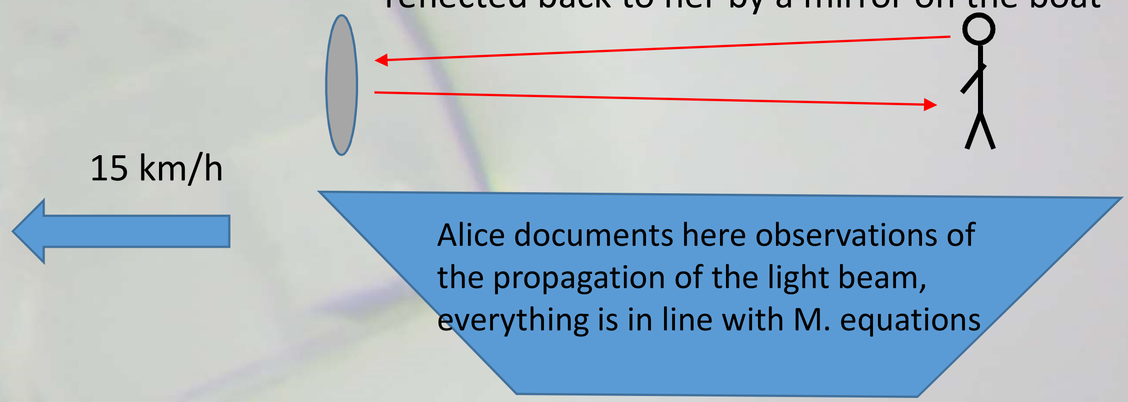
Where did his come from ?

Classical mechanics:

$$\vec{p} = \mathrm{m} \cdot \vec{v}$$

$$\vec{F} = \frac{\partial \vec{p}}{\partial t} = \mathrm{m} \cdot \vec{a}$$

Women induces an electromagnetic wave, reflected back to her by a mirror on the boat



This apparently "logic" addition of velocities does not work for electrodynamics

Applying a linear (Galileo-) transformation, Paul should not observe the same phenomenon. M. equation seem invalid.

Electrodynamic intermezzo

To “save” the validity of Maxwell's equations (or at least their use for practical reasons), H. A. Lorentz proposes to use a different transformation than the linear Galilei one.

This “Lorentz transformation” was considered a mathematical trick to get back to work eventually until the correct equations describing electromagnetism would be found.

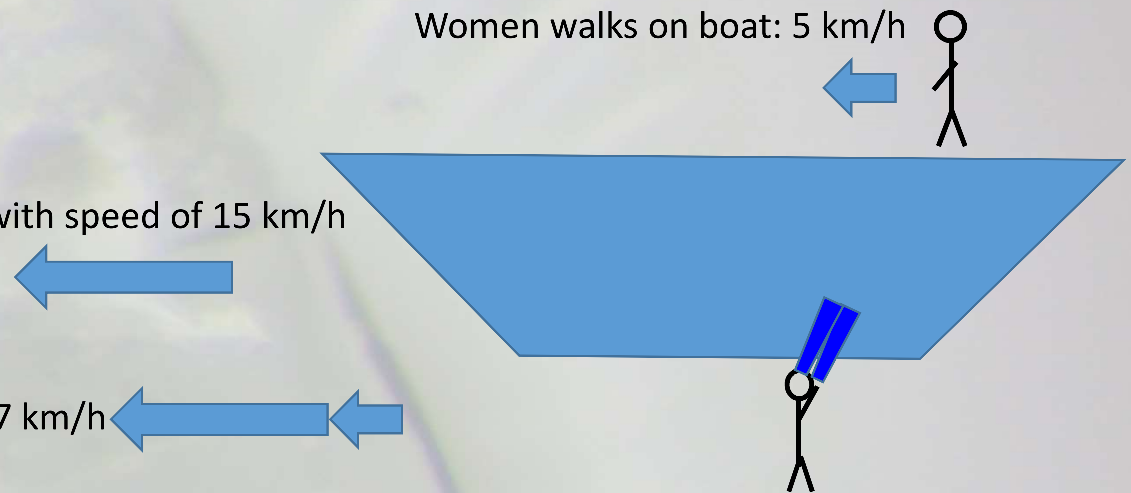
A. Einstein proposes to apply the Lorentz transformation as the only valid one discarding classical mechanic as “wrong”. This requires to claim

1. That the vacuum speed of light is a natural constant and
2. That every observer measures the same speed of light

As part of the physical reality. It unavoidably leads to a “deformation” of space and time thus affecting also basic mechanical properties
(*the world is not as simple as we tried to make it*)

Lorentz transformation of reference frames

What was supposed to mathematically treat electromagnetism, while waiting for its better understanding, "destroyed" classical mechanics



Relativity links space and time to the observer.
From the various equations a useful **Lorentz factor γ** can be defined as:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{mc^2}$$

Womans' relative motion to observer : $v_{obs} = \frac{v_1+v_2}{1+\frac{v_1 \cdot v_2}{c^2}}$

(Lorentz transformed motion)

For linear motion, γ is the factor by which space contracts and by which time gets dilated.
At *v=0.995 c* (99.5 % speed of light) $\gamma = 10$
-> time "slows down" by a factor of 10 relative to observer "at rest"
& space contracts by a factor of 10 fro observer at rest

Electrodynamic intermezzo (last slide)

Larmors formula (19th century):
irradiated power by *accelerated* charges:

$$P = \frac{2}{3}\frac{e^2}{c^3}\left|\dot{\vec{v}}\right|^2$$

Relativistic version Linear motion (total power): $P = \frac{2}{3}\frac{e^2}{c^3}\left|\dot{\vec{v}}\right|\gamma^6$

Circular motion (in bends): $P = \frac{2}{3}\frac{e^2}{c^3}\left|\dot{\vec{v}}\right|\gamma^4$

classical consideration : $\gamma = 1$

20-100 kV (“TV”, Lab source electron gun): $\gamma \approx 1.05 \ldots 1.2$

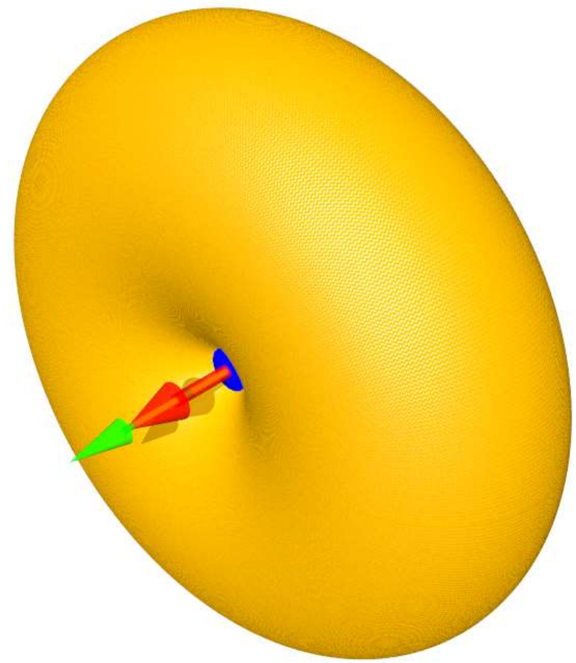
Synchrotrons ESRF (6 GeV): $\gamma = 11750 \sim 10^4$

Light emission by accelerated charges

Directional emission characteristics by an accelerated charge (dipole-radiation)

Classical result (Linear acceleration):

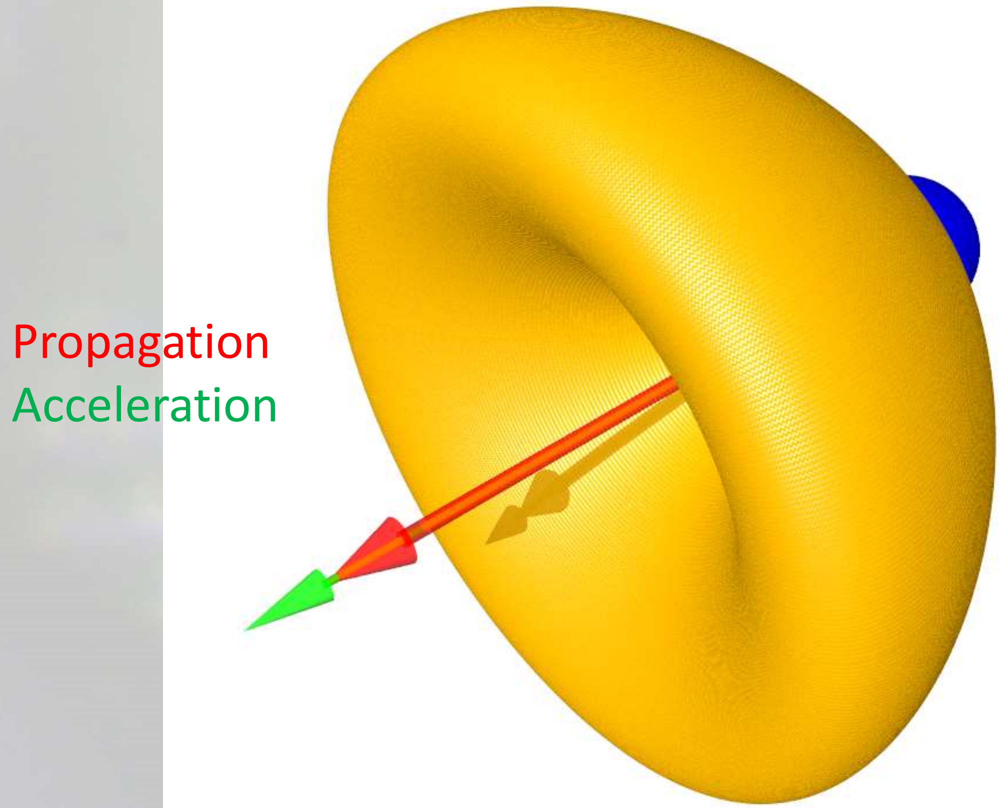
Propagation
Acceleration



Light emission by accelerated charges, as seen by observer

Directional emission characteristics by an accelerated charge (dipole)

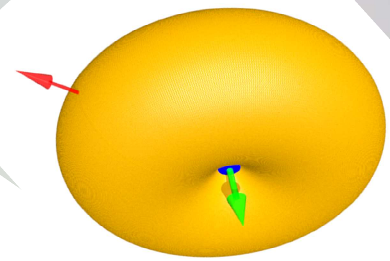
Relativistic (Bremsstrahlung from X-ray tube, Cathodic tube):



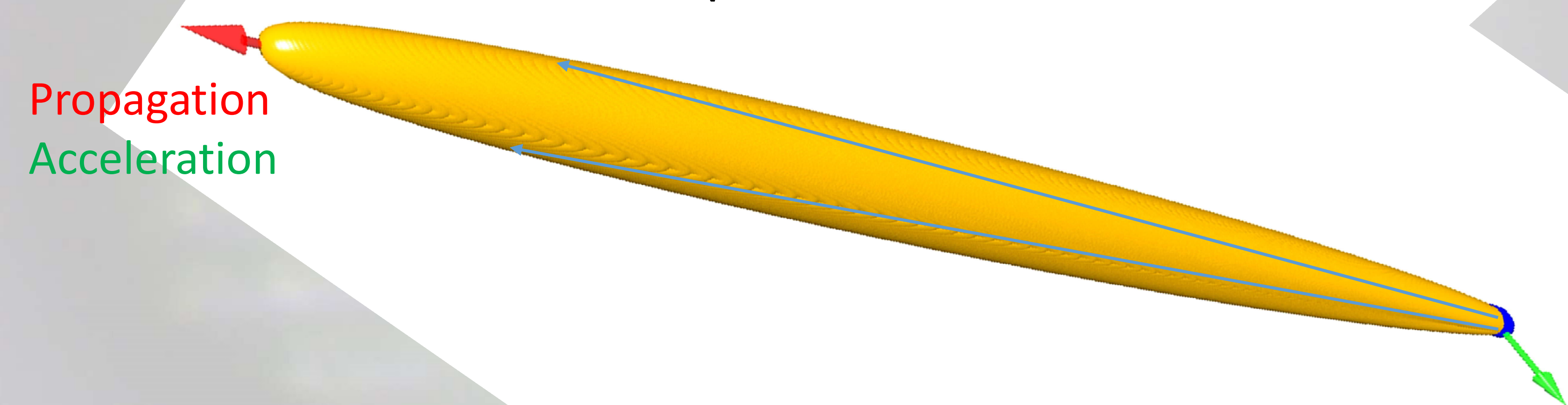
Light emission by accelerated charges, as seen by observer

Directional emission characteristics by an accelerated charge (dipole)

Highly relativistic case & circular motion



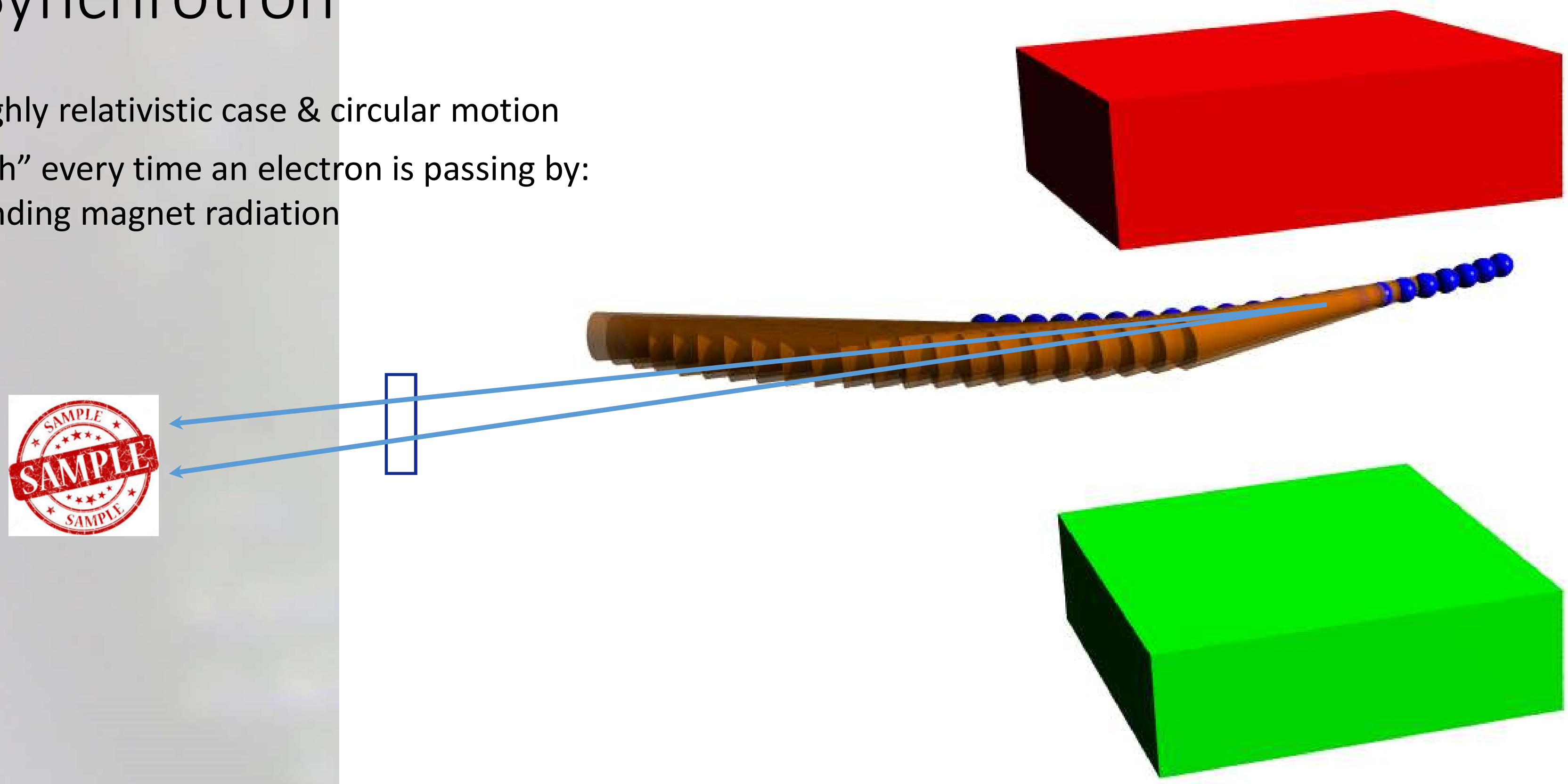
Opening angle $^{2}/_{\gamma}$ (=0.01° for $\gamma = 10^4$)



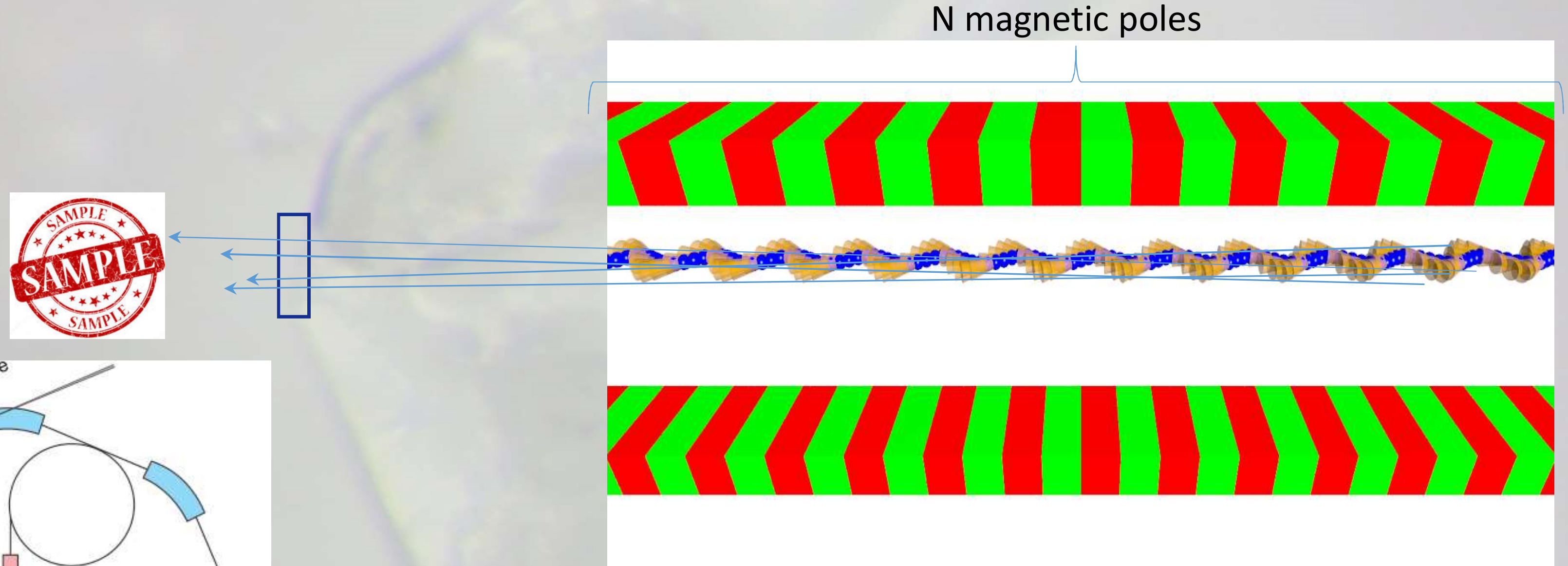
Light emission by accelerated charges: Bending Magnet of a Synchrotron

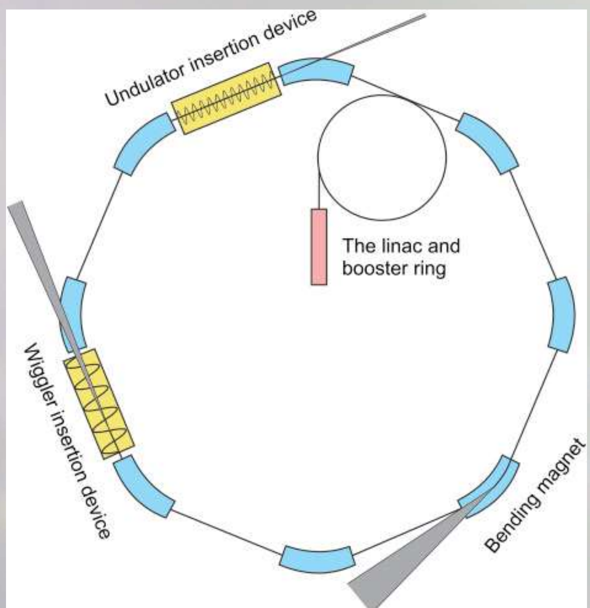
Highly relativistic case & circular motion

“Flash” every time an electron is passing by:
“ Bending magnet radiation



Synchrotron Radiation from insertion devices





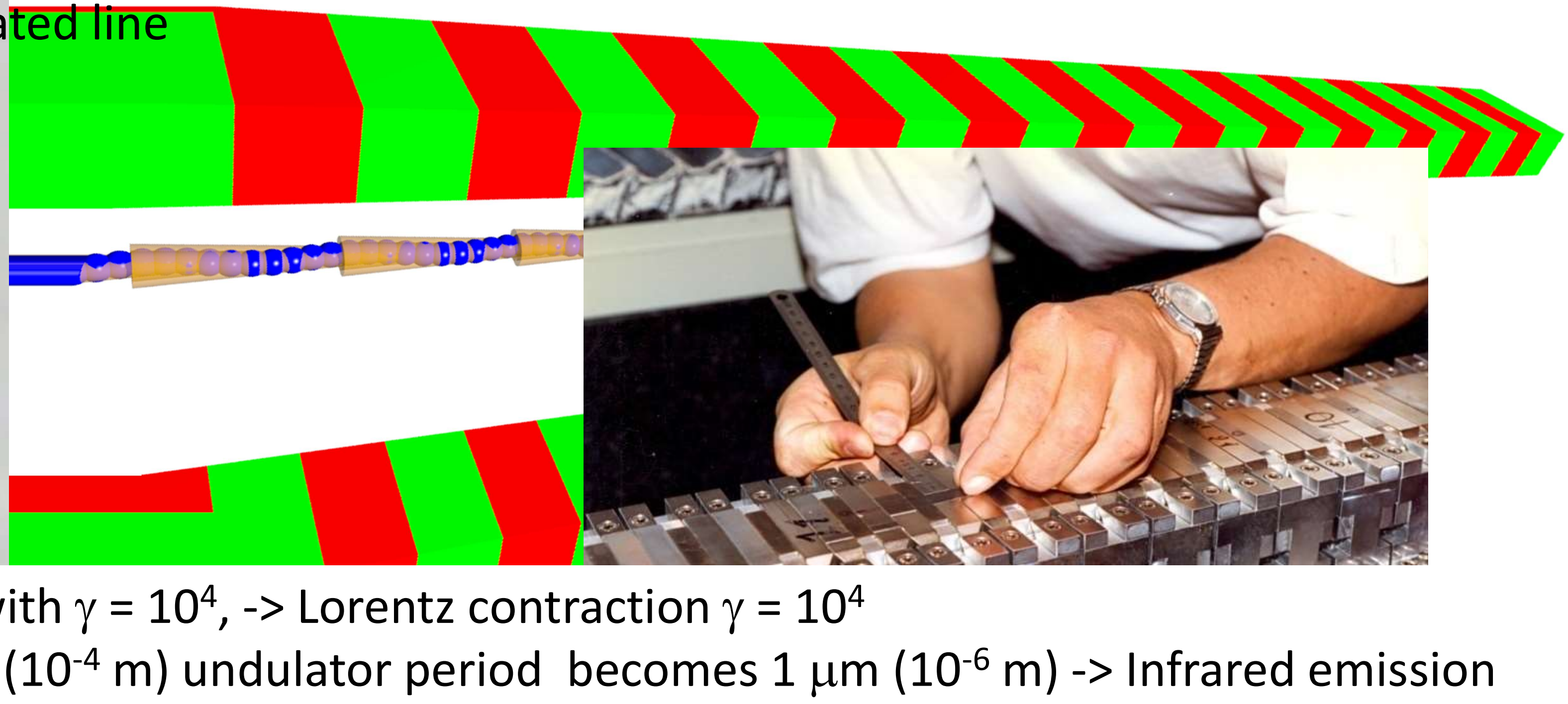
Wigglers: sum of N bending magnets: gain = N

Undulators as insertion devices

Undulators: angular deviation < ${}^{2}/_{\gamma}$ -> coherent superposition of emitted light gain= N^2

Supplies a self collimated line spectrum

Wavelength ?



Electrons rushing by with $\gamma = 10^4$, -> Lorentz contraction $\gamma = 10^4$
For the electrons 1cm (10^{-4} m) undulator period becomes 1 μm (10^{-6} m) -> Infrared emission

Sample is standing still with respect to electrons
-> Doppler effect of light ("blue shift") 10^{-6} m -> $0.5*10^{-10}$ m = X-rays

Evolution of Synchrotron radiation: 12 orders of magnitude in 35 years

Smal beam & “parallel” emission = super brilliant

Time structure of the beam: All synchrotrons are pulsed sources (electrons travelling in ~10^{-10} s bunches).

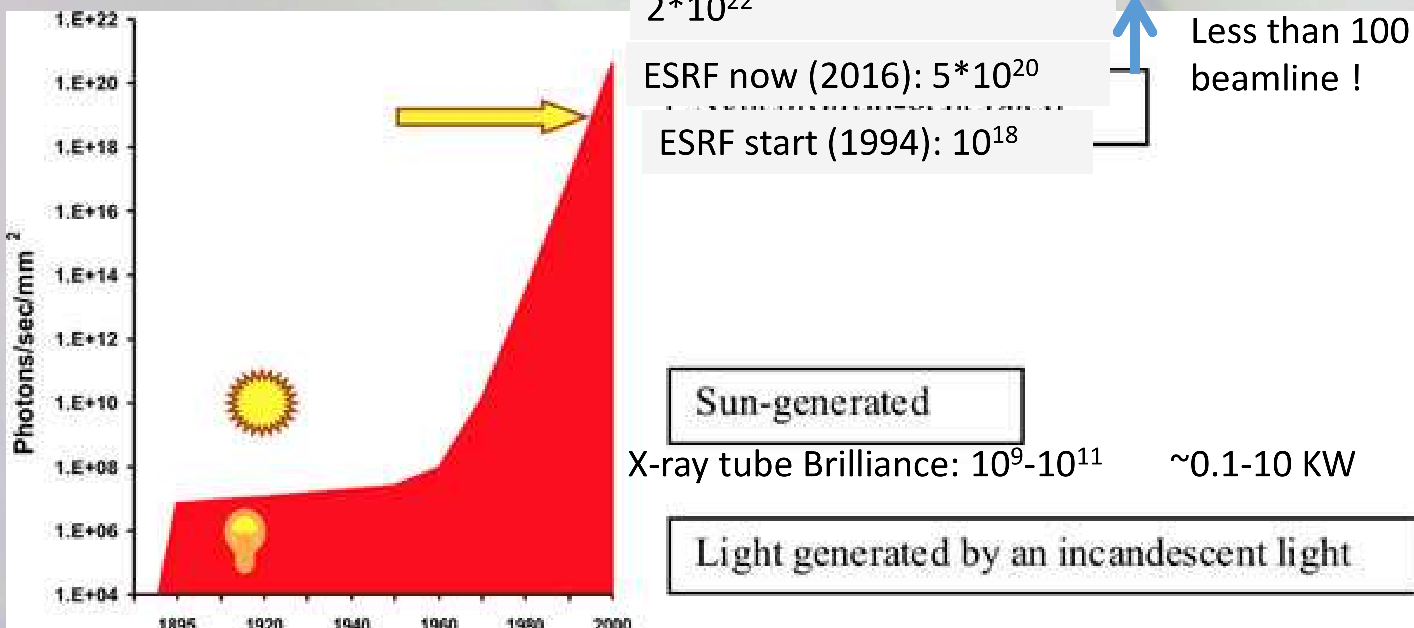
$$\text{brilliance} = \frac{\text{photons}}{\text{second} \cdot \text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\%\ \text{BW}}$$

ESRF “Extremely Brilliant Source” Project EBS (2020): $2*10^{22}$

ESRF now (2016): $5*10^{20}$

ESRF start (1994): 10^{18}

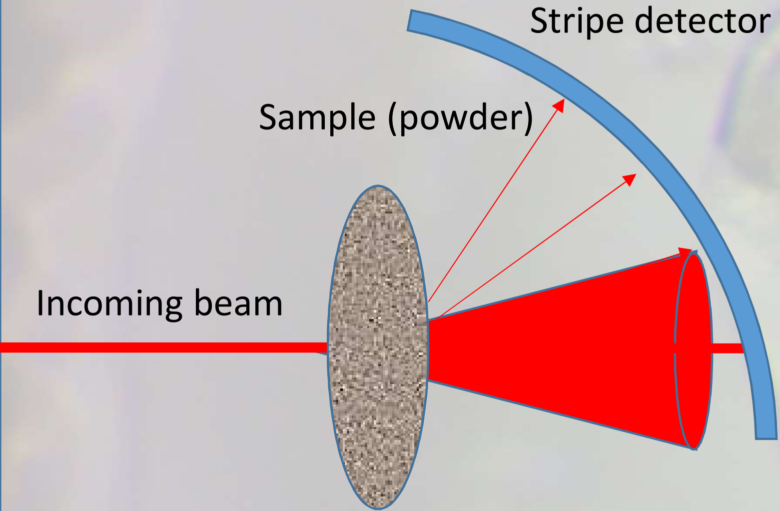
Reduction of power from 5 MW to 3 MW:
Less than 100 kW per beamline !



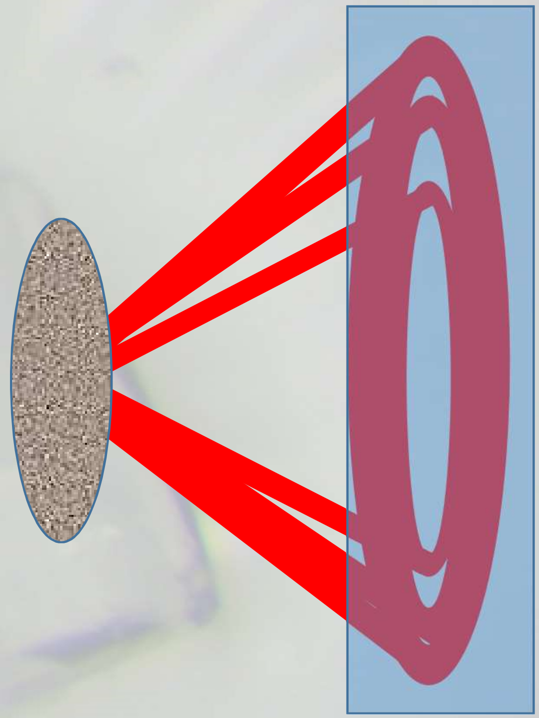
X-ray tube Brilliance: 10^9-10^{11} ~0.1-10 KW

Brilliance and powder diffraction

Advantage 1: transmission geometry and low divergence allow for simultaneous collection of multiple Bragg peaks

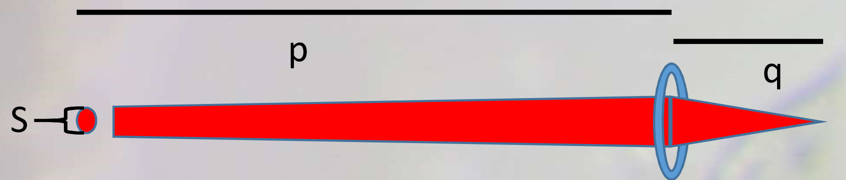


In reality: intensity from a powder is emitted in a cone; the stripe detector is cutting out a small part of it



A flat 2D detector ("Camera") cold detect the complete beamcone, increasing by a factor of 100-1000 the detected flux, eventually sacrificing range in reciprocal space

Brilliance spatial resolution



Small source + low divergent beam: even 20-30 m from the source, the beam cross section is small
-> it fits even in the small aperture X-ray optics we have (or at least a reasonable fraction of the beam)

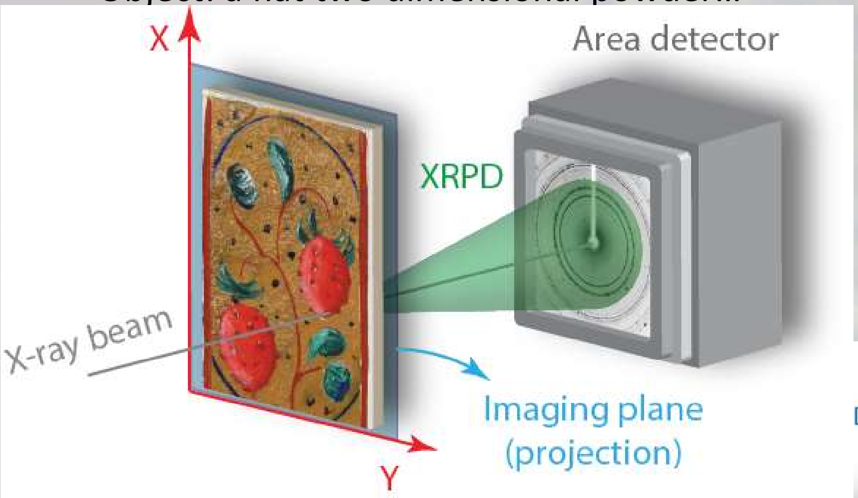
Beam can be focused into a spot of size S*q/p:

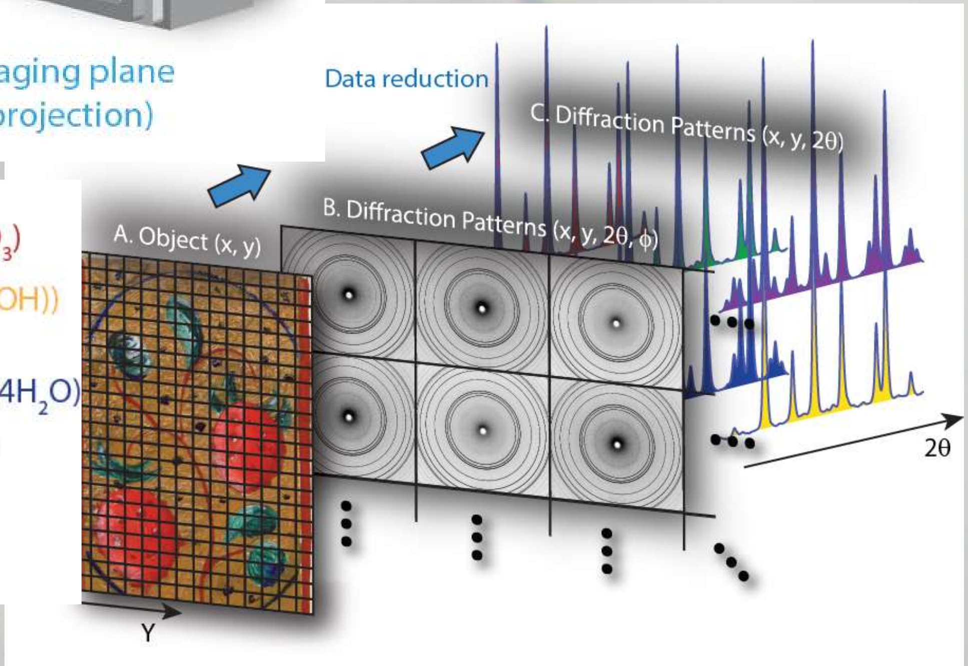
As a minimum of space is required around the sample an easy way to make small beams is to make p really long

Scanning small beams….

Object: a flat two dimensional powder…

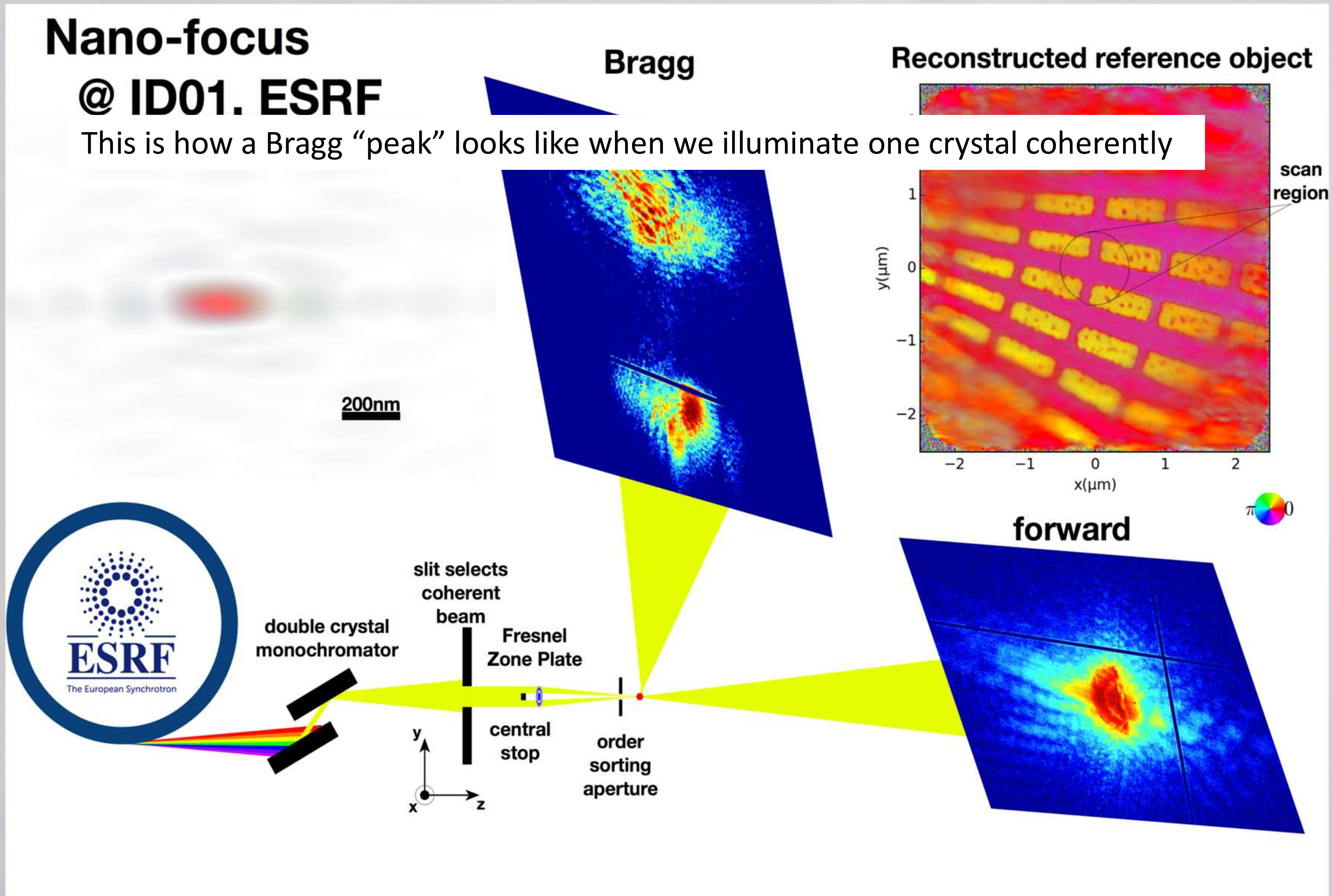
Slide courtesy: W. De Nolf, M. Cotte (ESRF, ID21)



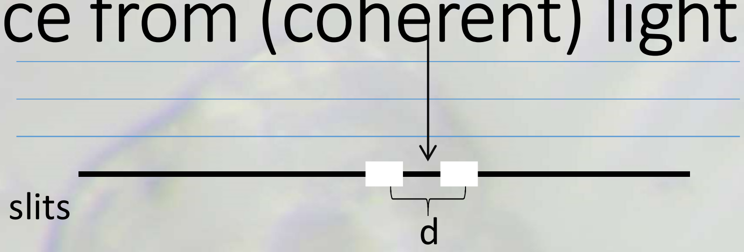


CDI: we need coherent light for our reconstruction

This is how a Bragg “peak” looks like when we illuminate one crystal coherently

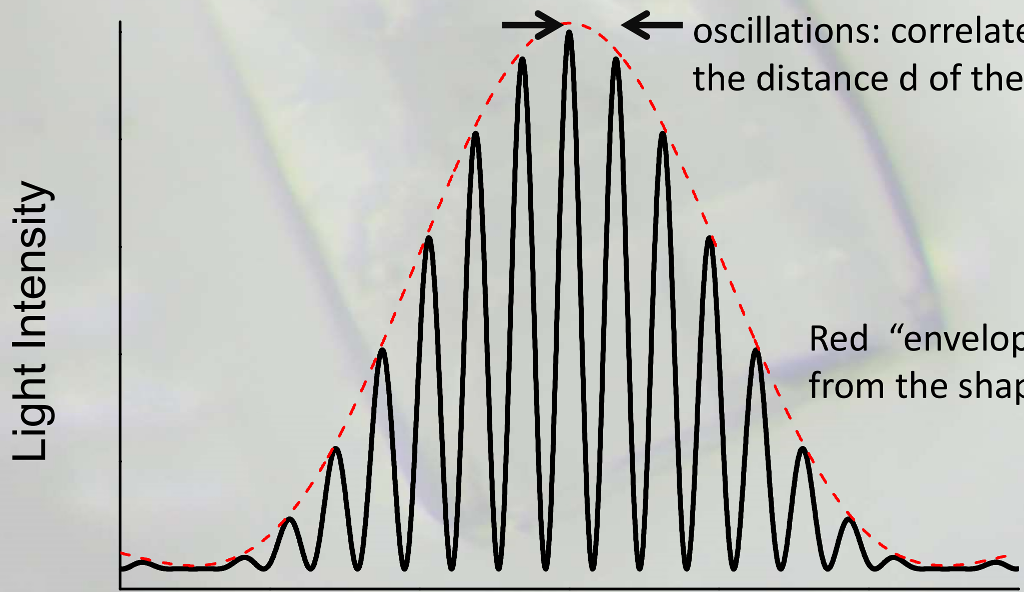


Interference from (coherent) light waves



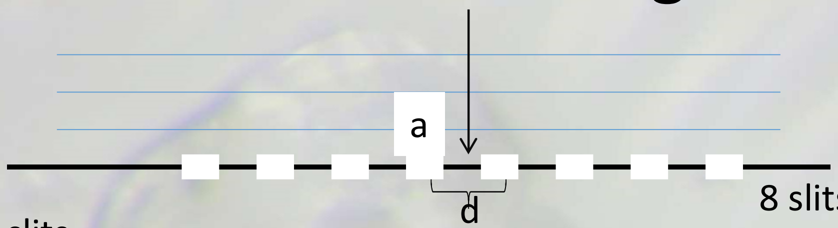
d: distance between two slits
N=2 (number of slits)

Distance between oscillations: correlates to the distance d of the slits



Red "envelope": originates from the shape of one slit

Interference from coherent light waves

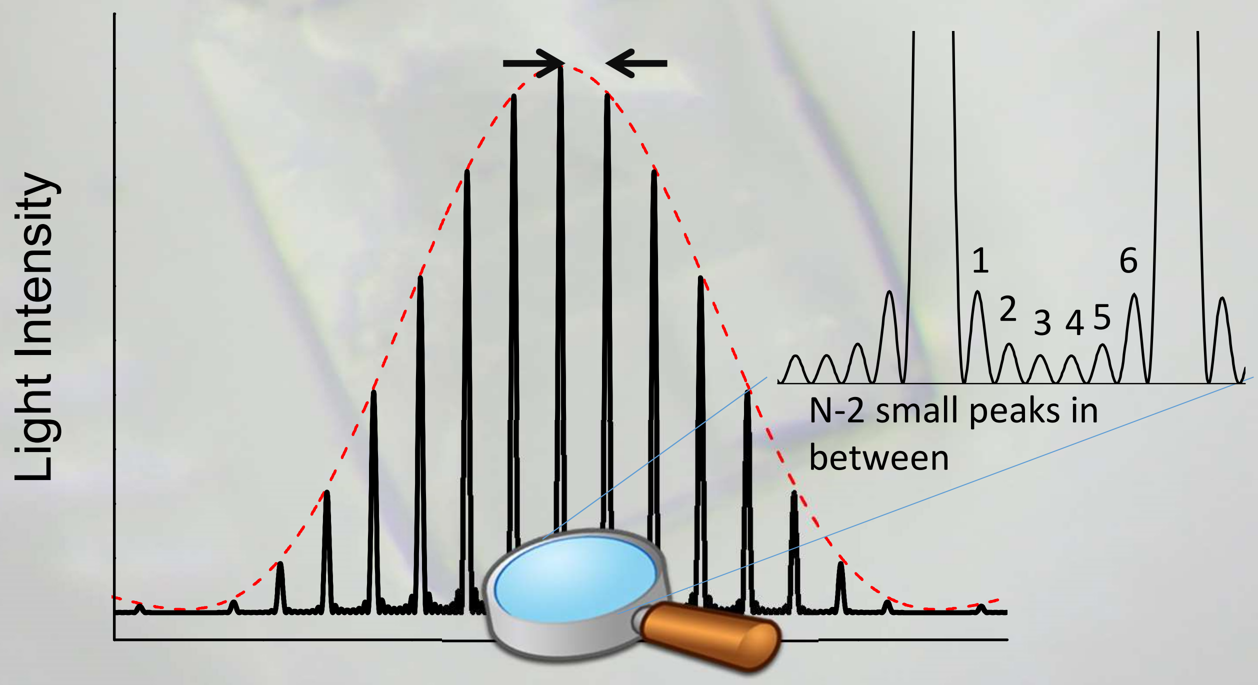


8 slits instead of 2

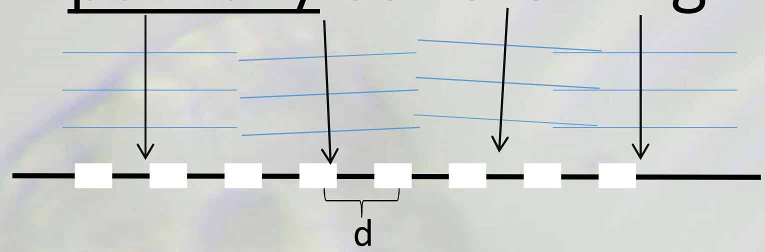
a: size of one slit

d: distance between 2 slits

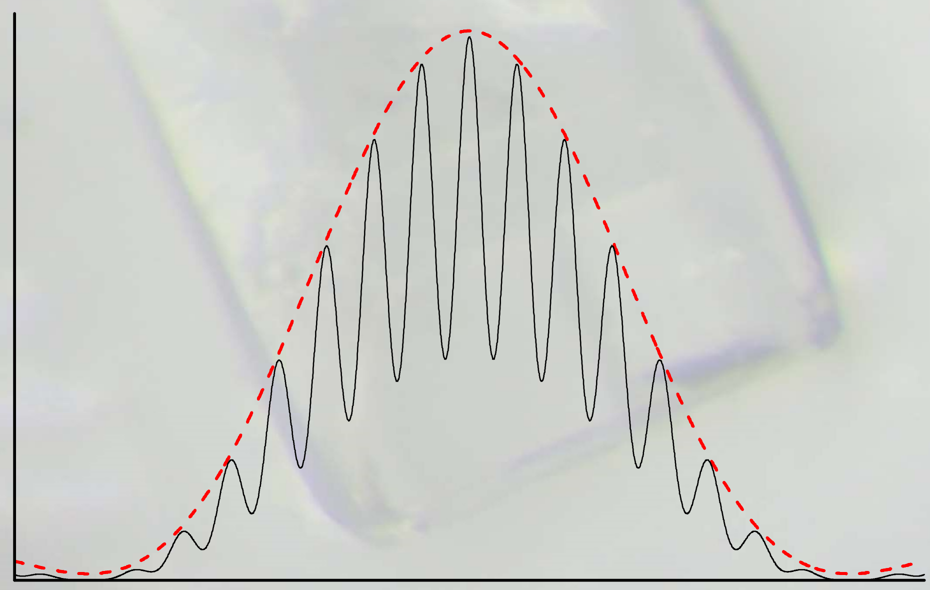
Number of slits N=8



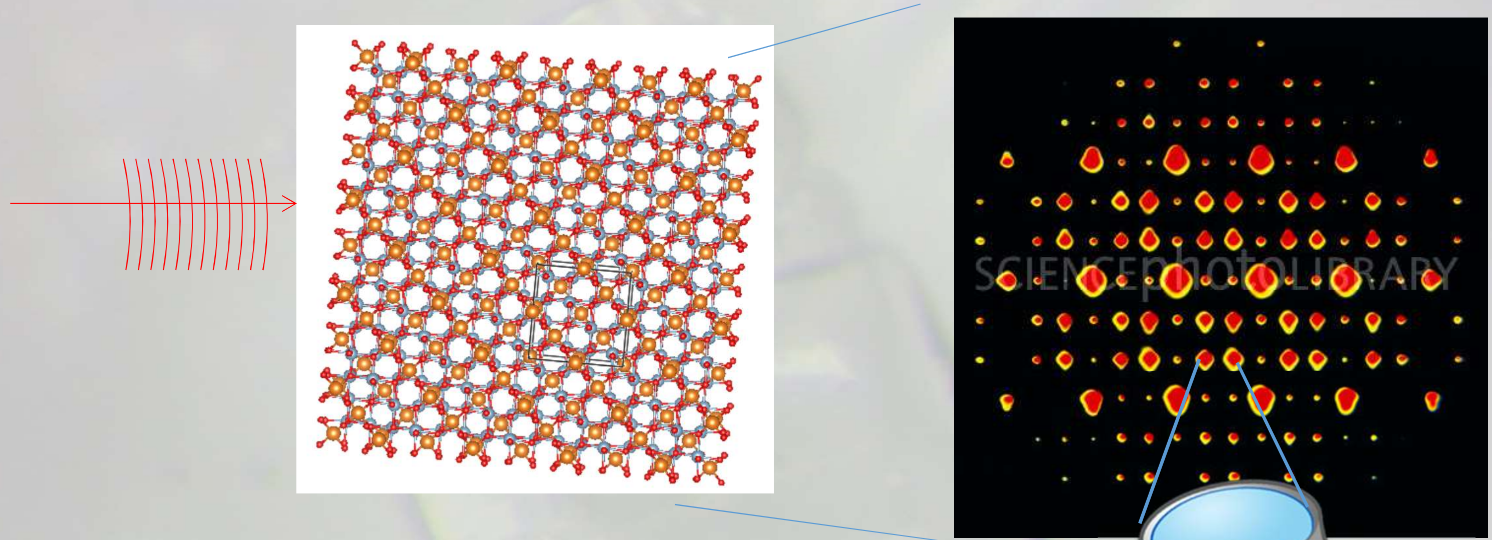
Interference from partially coherent light waves



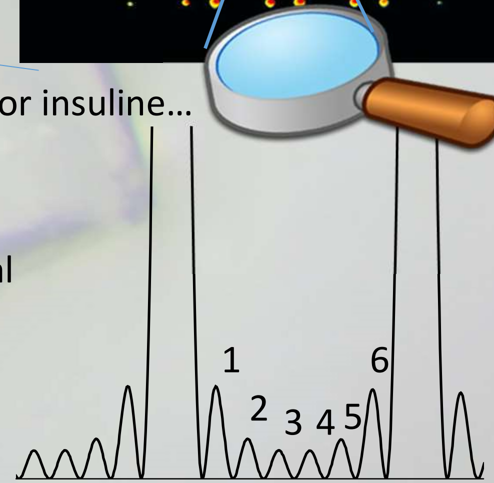
Coherence length L ~d:
scattering looks like from 2 slits



(Coherent) X-ray diffraction from a crystal



The “big” peaks tell me “it is quartz” or gold or iron… spinell or or insuline…
-> Material science



The small peaks allow me to extract the exact picture of my nano crystal

N-2 small peaks in between